PS Tectonic and Eustatic Controls on Internal Architecture and Stacking Patterns of Pleistocene Shallow-Marine and Fluvial Depositional Sequences*

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Abstract

The complex interaction of regional uplift, glacio-eustasy, local tectonics, and sediment supply has a significant impact on the internal architecture and vertical arrangement of shallow-marine and fluvial depositional sequences and can be documented in well-exposed successions of Pleistocene strata cropping out along the uplifted margins of Ecuador, northern Chile, and eastern central Italy.

The results stemming from these sediments have important implications for sequence stratigraphic models in tectonically active areas and lead to the following general conclusions: (i) given that rates of syndepositional regional tectonic uplift were substantially less than rates of contemporaneous eustatic changes in sea level in all of the study areas, glacio-eustasy appears to have played the main control on development of high-frequency sequences; (ii) stratal geometries, sedimentary facies, and genetic complexity of sequence bounding unconformities of these cyclic successions indicate that the internal organization of individual depositional sequences is directly controlled by the rates of sediment supply and by the occurrence of intrabasinal, short-term normal faults striking obliquely with respect to paleo-shoreline trends; (iii) the effects of the regional tectonic uplift on these eustatic sequences is on longer term, at sequence set scale, and is responsible for their distinctive stacking pattern; owing to the progressive, tectonically driven reduction of accommodation space, high-frequency sequences are nested within a forced regressive sequence set, where each successively younger sequence is displaced basinward and downward respect to the last.

TECTONIC AND EUSTATIC CONTROLS ON INTERNAL ARCHITECTURE AND STACKING PATTERNS OF PLEISTOCENE SHALLOW-MARINE AND FLUVIAL DEPOSITIONAL SEQUENCES

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Ecuador: Canoa and Tablazo Formations

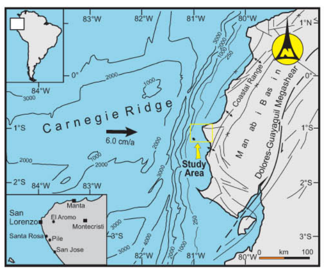


Figure 1a. Structural map of the Ecuadorian coast showing position of the study area (boxed part) with respect to the place where the Carnegie Ridge impinges on the Ecuador Trench.

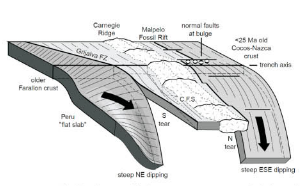


Figure 1b. 3-D view of the two-tear model for the Carnegie Ridge collision featuring: a steep ESE-dipping slab beneath central Colombia; a steep NE-dipping slab from 1ºS to 2ºS; the Peru flat slab segment south of 2ºS; a northern tear along the prolongation of the Malpelo fossil spreading center; a southern tear along the Grijalva FZ; a proposed Carnegie flat slab segment (C.F.S.) supported by the prolongation of Carnegie Ridge. (Gutscher et al. 1999).

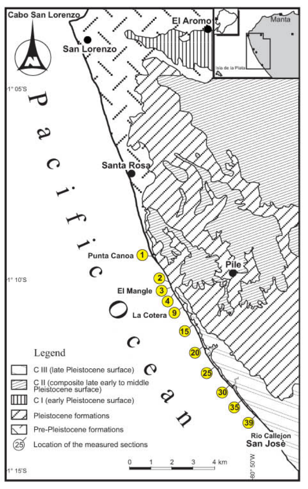


Figure 2. Detailed location map of the measured sections. Numbers and localities along the coast refer to measured sections shown in Figure 3.

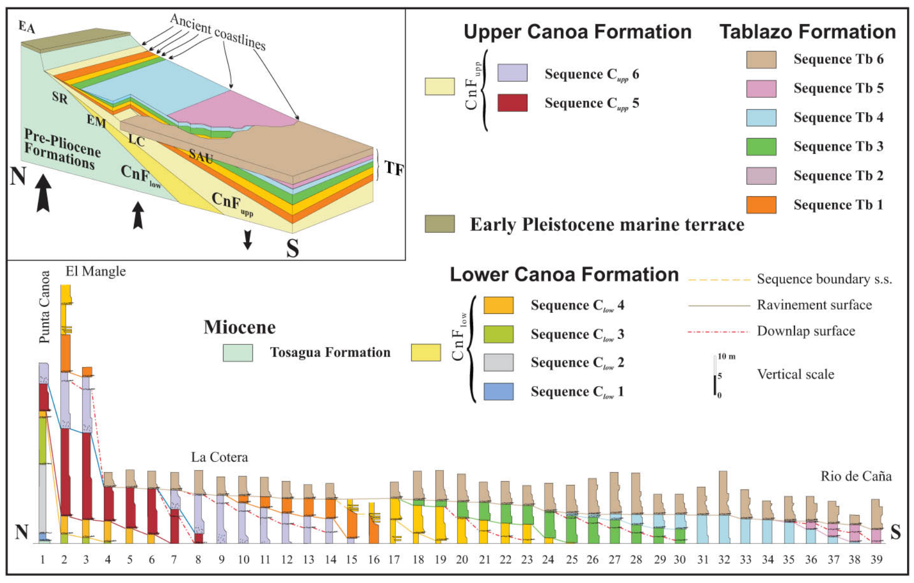


Figure 3. Schematic cross-sectional panel (see location of the 39 measured sections in Figure 2). The inset is a block diagram showing the stacking pattern of the Plio-Pleistocene depositional sequences. Arrows indicate uplift and subsidence. EA - El Aromo; SR - Santa Rosa; EL - El Mangle; LC - La Cotera; SAU - Syntectonic Angular Unconformity; CnF - Canoa Formation; TF - Tablazo Formation. Except for sections 1 and 2, and sections 15 and 16 that are about 1,5 km and 30 m apart, respectively, spacing between successive measured stratigraphic sections range from 200 and 250 m.

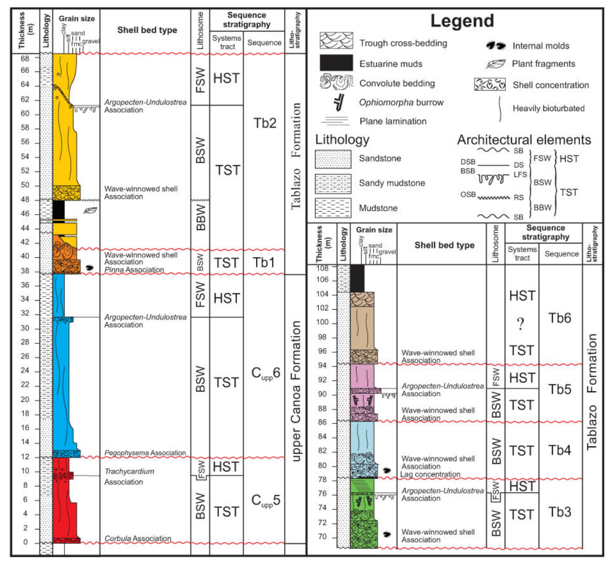
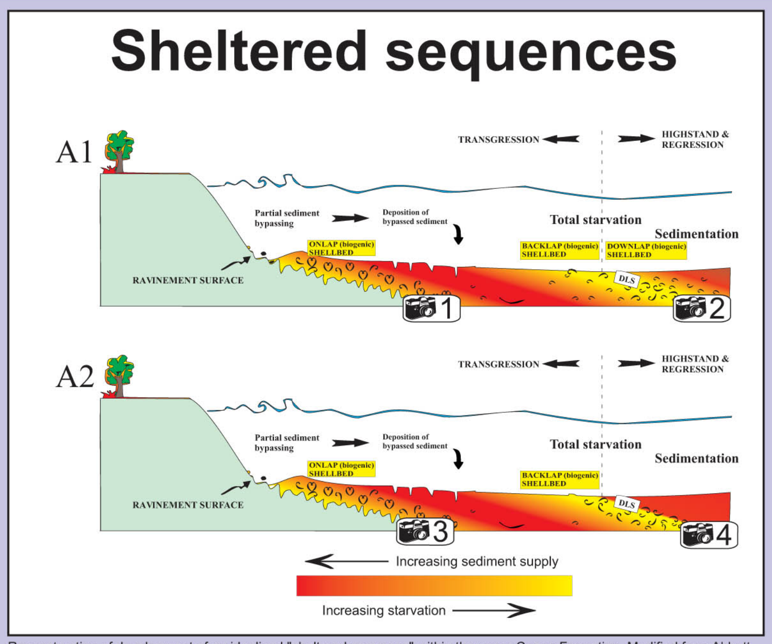


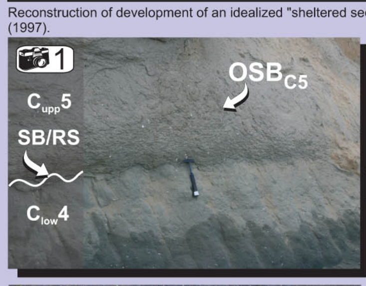
Figure 4. Composite stratigraphic section compiled for the Pleistocene sedimentary succession exposed between El Mangle and Rio Callejon (San José). The eight depositional sequences identified are subdivided in the component systems tracts. BBW, back-barrier wedge; BSW, backstepping shelf wedge; TST, transgressive systems tract; HST, highstand systems tract; DSB, downlap shell bed; BSB, backlap shell bed; OSB, onlap shell bed; SB, sequence boundary; DS, downlap surface; LSF, local flooding surface, RS, ravinement surface.

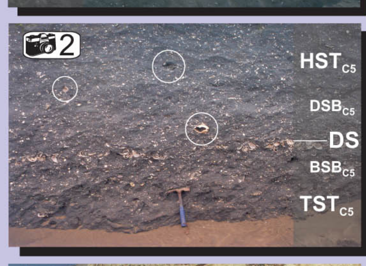
Control of coastline physiography on sequence architecture

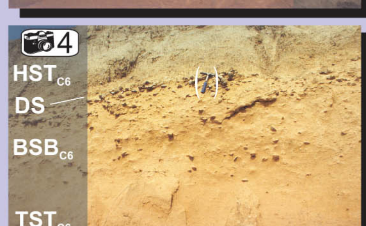
Sheltered sequences



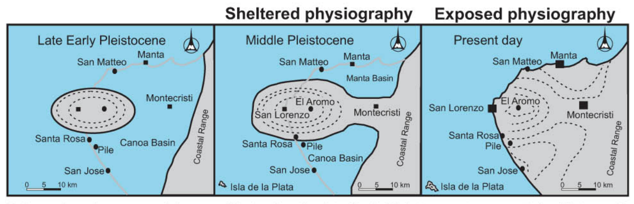
Reconstruction of development of an idealized "sheltered sequence" within the upper Canoa Formation. Modified from Abbott (1997).



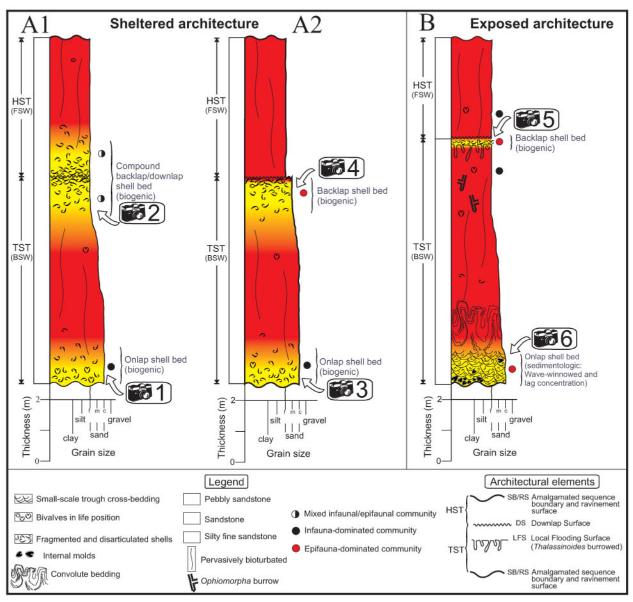




Outcrop photographs of the biogenic shellbeds occurring within sheltered sequences of the upper Canoa Formation. (2) Cross-section of the Trachycardium association present in mid-cycle position within sequence $C_{upp}5$ (compound BSB_{C5}/DSB_{C5}). Notice, encircled, the presence of articulated and closed individuals of D. ponderosa with the commissure subparallel to bedding but displaced from their life position and the high concentration of concave-up valves of T. procerum along the omission (downlap) surface. Also note the gradual transition with the encasing sediments. (3) Cross-section view of the Trachycardium (DSB_{C5}) and Pegophysema association (OSB_{C6}). Note the relatively low density of shells. (4) Cross-section through the Argopecten-Undulostrea Association (BSB_{C6}). Notice the shellier upward biofabric, the gradual transition with the underlying sediments, and the sharp contact (downlap surface) with the overlying HST shelf siltstones and muddy fine sandstones.

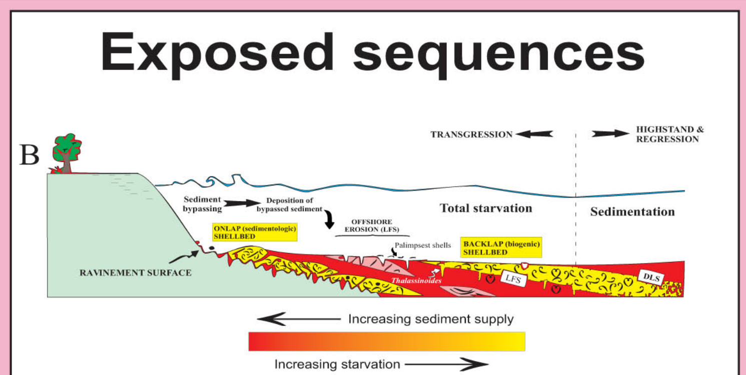


Schematic paleogeographic maps illustrating the late Early Pleistocene to present-day history of the Cabo San Lorenzo area. Solid gray line = present coastline. Dashed lines = location of uplifted coastlines.

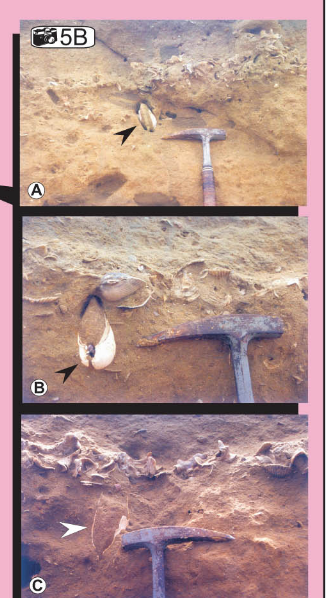


Idealized lithologic logs contrasting the main features of (A) sheltered and (B) exposed sequence architecture. Sequences with a sheltered architecture developed in a shelter, semi enclosed basin. They are characterized by highly bioturbated transgressive shelf wedges that are underlain by little-transported, low-density and infauna dominated community onlap shell beds and grade up into shellier-upward community backlap shell beds composed of mixed shallow infaunal/epifaunal benthos or dominated by epifaunal taxa. Sequences with an exposed architecture developed in a more open setting. Their deposits show high-energy features, such as trough-cross stratified wave-winnowed and lag concentrations formed by storm waves and currents along the bases of the transgressive shelf-wedges, storm-wave related soft-sediment deformation structures, and a sharp, variably burrowed erosional transition between the siliciclastic shelf wedges and the overlying late transgressive, epifaunal-dominated community backlap-shell beds.

Exposed sequences

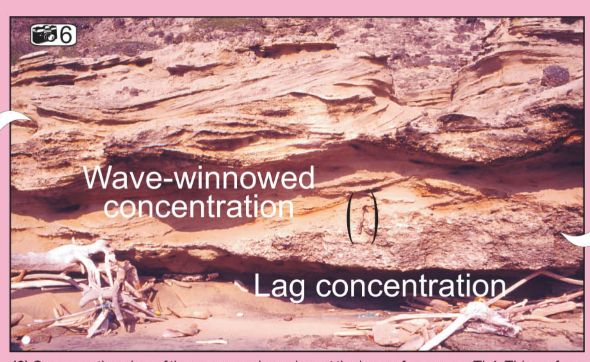


Reconstruction of development of an idealized "exposed sequence" within the Tablazo Formation. Modified from Abbott (1997).



(5A) Northward view of the sequence Tb2. Note the progressive southward (toward the right) erosion at the LFS of the 2.5-m-thick sediments indicated with the white arrowed brackets at the left of the picture. (5B) Close views of biogenic shell beds within the Tablazo Formation. (A, B) Some of the individuals of the shallow burrowing, siphonate suspension-feeding bivalve *D. ponderosa* (arrowed) are found lying normal to the bedding plane, with the commissure plane and the antero-posterior axis oriented vertical (upright), and the umbo pointing laterally or slightly downward. (C) White arrows indicate life-oriented individuals of *Panopea* sp. just below BSB_{T2}. It is important to note that components of shell-gravel-dwelling epifauna occur only within the backlap shell bed, whereas the relatively shell-poorer encasing sediment is characterized by the sporadic presence of a dominant soft-bottom infauna mostly preserved in life position and includes relatively deep-burrowing forms.

Plane view of a trough cross-bedded, wave-winnowed shell assemblage. The erosive contact with the underlying sequence is indicated by arrows. Shells are finely fragmented, densely packed and highly abraded.



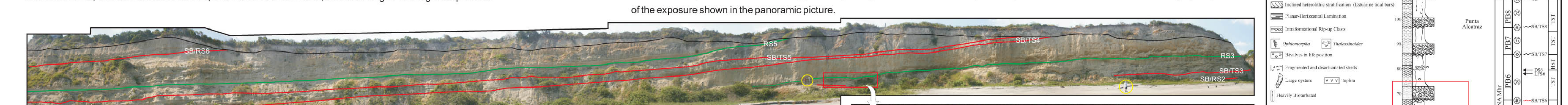
(6) Cross-section view of the sequence boundary at the base of sequence Tb4. This surface, erosive into the underlying deposits, is discontinuously mantled by a lag concentration that, in turn, is sharply and erosively overlain by a trough cross-bedded wave-winnowed shell bed. The contact is just above the hammer (in brackets).

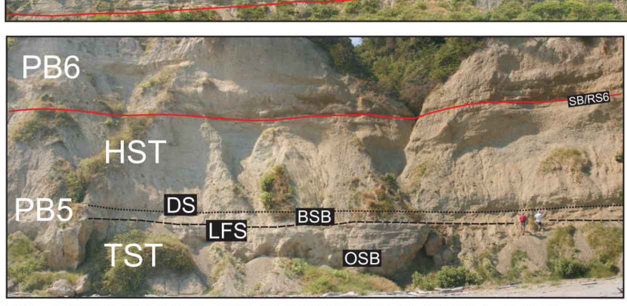
Bedding view of the lag concentration at the base of sequence Tb4. Mollusk preservation is exclusively as mud- or silty filled internal molds of fossils, including those of the venerid D. ponderosa, which are presumably supplied to the concentration through the process of shoreface erosion.

Ecuador: Jama Formation

Panoramic view of the middle portion of the Punta Ballena Member (Jama Formation). The succession was deposited in shallow-marine, tide-dominated estuarine, and fluvial environments, and is arranged into eight sequences.

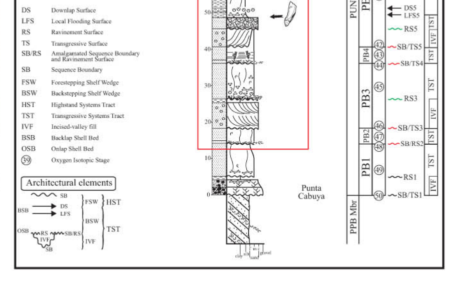
Composite stratigraphic section for the Lower Pleistocene sedimentary succession exposed between Punta Cabuya and Punta Alcatraz (Punta Ballena Member). The eight depositional sequences identified are subdivided into component systems tracts and tentatively correlated with the oxygen isotope time scale. Since a single sequence and associated lower boundary should represent a glacial-interglacial stage couplet, they seem to correspond to the record of oxygen isotope stages 35-49 defined in deep sea deposits. The red box indicates the stratigraphic position of the exposure shown in the panoramic picture.





TST successions are capped by mid-cycle condensed shellbeds (BSB) that represent terrigenous sediment starvation at the seaward feather-edge of TST deposition and form at the TST/HST boundary. The upper contacts (downlap surface) are sharp transitions from shell-rich to relatively shell-poor lithofacies of overlying HST shelf siltstones and muddy fine sandstones.

Sequences in the Punta Ballena Member are composed of TSTs and HSTs. Above a basal cycle-bounding erosional unconformity, a typical sequence begins with relatively discontinuous inclined heterolithically stratified (IHS) mudstone and very fine to fine-grained sandstone that are interpreted as estuarine tidal bars. These sediments are truncated by a wave ravinement surface that is mantled by a pebble lag of rip-up clasts and fossils (onlap shell bed) that, in turn, is overlain by a fining-upward succession of lower shoreface bioturbated sandstones and inner-shelf siltstones and silty fine sandstones.



Short- and long-term tectonic control on internal architecture and stacking pattern of Pleistocene shallow-water and continental sequences (Qm2 and Qc Units, central Italy)

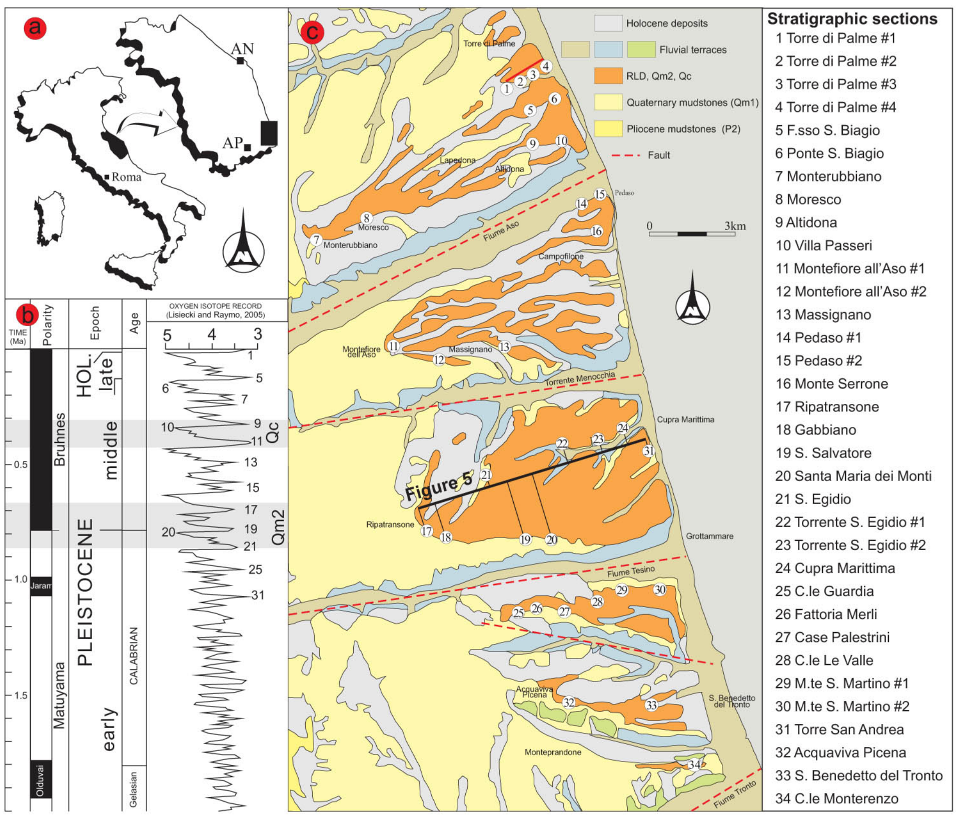


Figure 1. (a) Study area. (b) Adopted time framework. (c) Detailed location map of the measured sections.

The youngest portion of the Peri-Adriatic basin fill, eastern central Italy, is subdivided into three tectonically induced units recording an overall shoaling-upward evolution from open-marine (Qm1) through nearshore (Qm2) to fluvial deposits (Qc). This trend reflects regional uplift of the region, ultimately leading to emergence, combined with the contemporary Quaternary glacio-eustatic sea-level fluctuations. The stratigraphic units described in this area readily lend themselves to a sequence stratigraphic interpretation and occurrence of high-frequency unconformities enables the splitting up of Qm2 and Qc into a stack of depositional sequences, each of which represents a single glacio-eustatic change in sea-level (Cantalamessa & Di Celma 2004). In total, at least five of such sequences have been recognized (Qm2 contains at least three and Qc contains two). The stratigraphic expression of these cycles varies, with the lower Qm2 sequences being distinctly different from the upper Qc sequences. Qm2 is late Early to early Middle Pleistocene in age and includes incised-valley fills, retrograding paralic systems, and both littoral and alluvial deposits. Qc is far from being fully exploited and a detailed chronostratigraphic framework is still lacking. A series of evidence, however, suggests that sedimentation took place during the Middle Pleistocene, possibly during MIS 9 and MIS 11. The Qm2-Qc sedimentary succession provides an unparalleled opportunity to examine the relationships between glacio-eustatic oscillations in sea-level, climate change, and sedimentary cyclicity. Based on the available chronostratigraphic data, the stratigraphic record of Qm2 covers part of the Early-Middle Pleistocene transition (Head and Gibbard 2005), sometimes known as the 'mid-Pleistocene revolution'. This time interval, ranging from MIS 36 (c. 1.2 Ma) to MIS 13 (c. 540-460 Ma), is marked by fundamental changes in Earth's climatic cyclicity and the glacial-interglacial world in which we now live is the result of these changes, which have had a profound effect on the biota and the physical landscape, especially in the northern hemisphere.

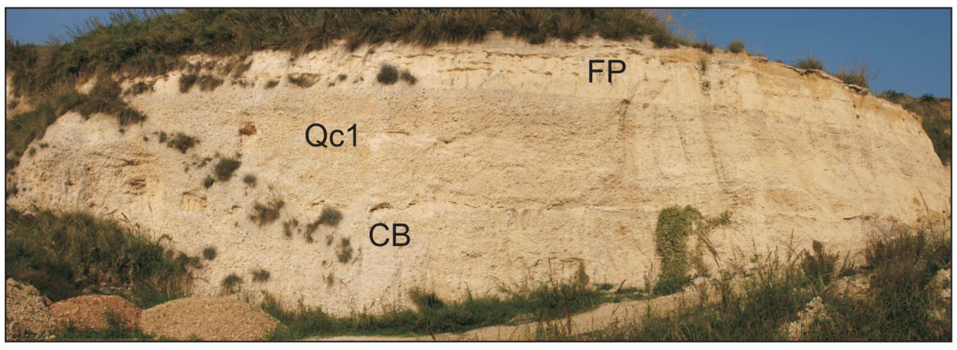
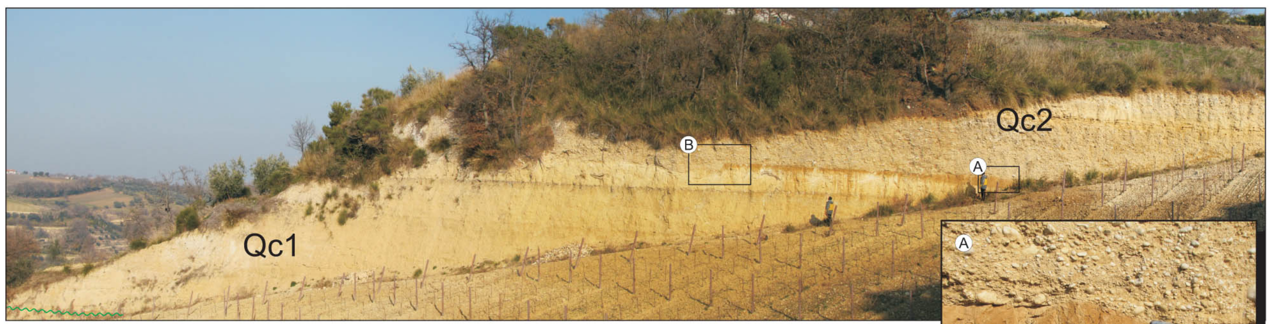
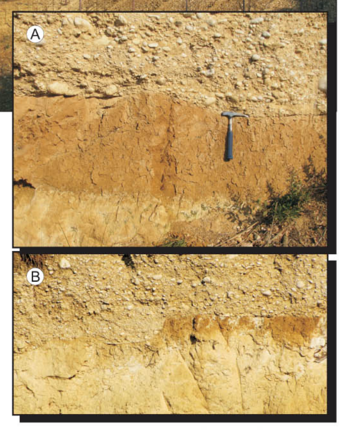


Figure 2. Fluvial deposits within the Qc Unit are generally separated into two main facies associations depending on whether they accumulated within the channel belt (**CB**) or on the floodplain (**FP**). Most conglomerates in the channel belt lack stratification (Gcm), though some display slight horizontal layering (Gh) or cross-bedding (Gp, Gt). The fine-grained overbank-floodplain facies association is built up of massive mud and silt (Fm) with minor laminated sand, silt and mud (Fl).

Qc Unit





The Qc Unit consists of two laterally continuous depositional sequences (Qc1 and Qc2), ranging from 10 to 25 m in thickness, and is characterized by fluvial deposits throughout its depositional history; however, due to changes in base level and the rate of creation of accommodation space, the fluvial style changes systematically and an idealized model of alluvial sequences can be established. In this model, a fully preserved alluvial sequence is expressed as a paleosol-bounded fining-upward succession of braided fluvial gravels and floodplain mud and sandy silt capped by a reddish paleosol. The basal package is composed of laterally stacked channel-fills with little preservation of fine-grained floodplain facies and suggests fluvial deposition in unconfined channel belts, possibly pebbly braidplain systems. This conglomerate-dominated package is succeeded by laterally extensive, fine-grained floodplain deposits with more isolated conglomerate bodies, and this interval may culminate in a reddish paleosol heralding the next phase of base-level fall and sequence-boundary generation. The red paleosols, which record sediment bypass during falling stage, lowstand and early transgressive systems tract time, do not appear to have formed under climatic conditions similar to those recorded in the Mediterranean area during the Holocene interglacial, evidencing a prolonged exposure to pedogenetic processes under pronounced humid and warm conditions. The gravel-prone intervals probably formed during periods of low accommodation creation and, accordingly, are related to periods with low rates of relative sea-level rise when the contemporary shoreline was several kilometers east of its present-day position. Architectural evolution including an upward increase in the preservation of floodplain units is considered to be due to higher rates of sea-level rise and an increase in generation of accommodation space. The paleosols at these sequence-bounding unconformities serve as useful regional stratigraphic markers to trace genetic packages across the basin and to determine regional accommodation trends. To the west (landward) the Qc1 paleosol is systematically replaced by a sharp erosion surface and the floodplain deposits exibit a marked thinning that is accomplished by erosional shaving of sequence top. These observations together suggest that this unconformity can be attributed to limited accommodation and erosion on the coastal plain during subsequent sea-level rise and requires synsedimentary uplift and tilting that progressively subtracted accommodation for sediments from east to west, producing an eastward divergence of sequence-bounding unconformities and hence a stratigraphic expansion of the succession in this direction.

Figure 3. The two insets (A and B) show details of the sequence boundary separating the two sequences of the Qc Unit. At this site, Qc1 is characterized by overbank deposits and a well-developed reddish paleosol that is succeeded abruptly (erosively) by the channel conglomerates of the next sequence. Traced laterally, the paleosol is discontinuous being in places cut out by the erosion surface. This paleosol formed in a floodplain environment and represent a widespread interfluvial (hiatus) surface indicative of extended subaerial exposure, pedogenesis and/or possible erosion in between deposition of the two units.

Qm2 Unit

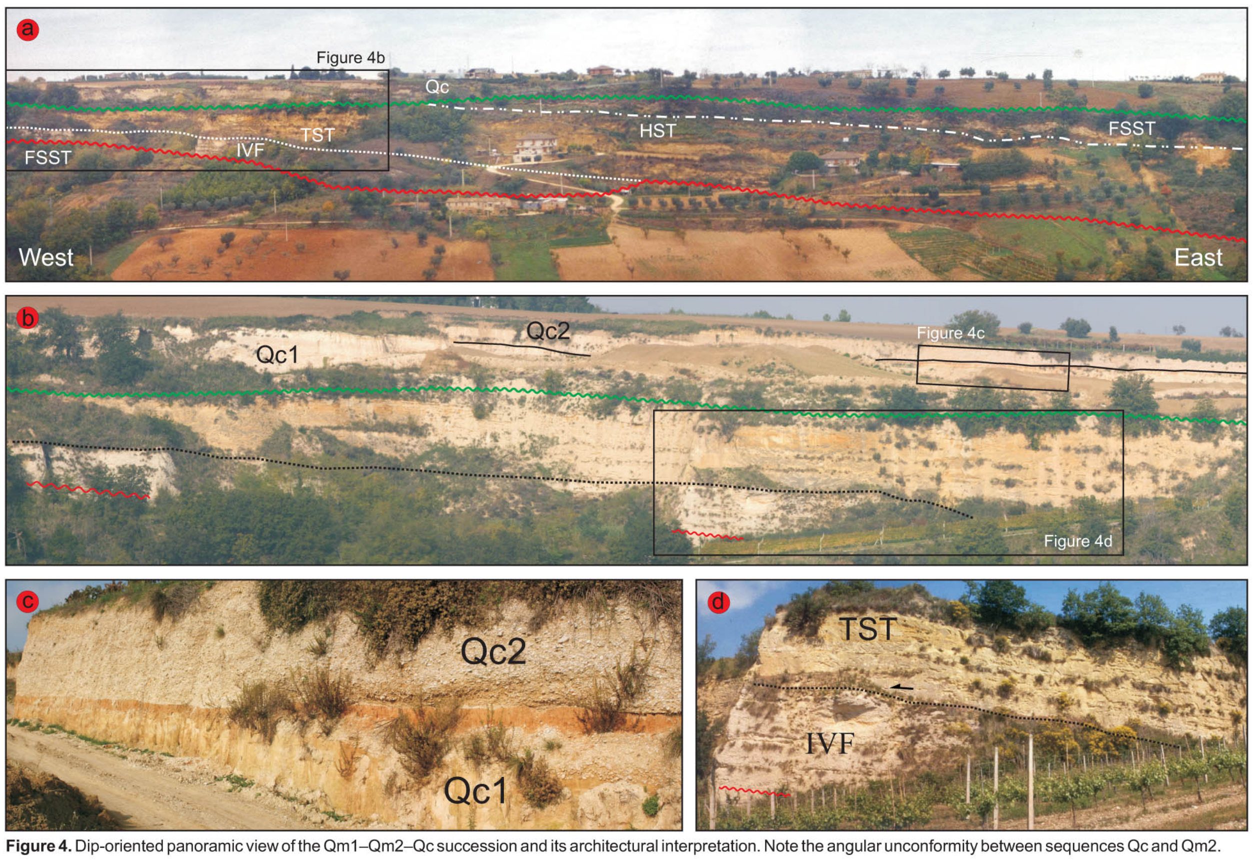


Figure 4. Dip-oriented panoramic view of the Qm1–Qm2–Qc succession and its architectural interpretation. Note the angular unconformity between sequences Qc and Qm2.

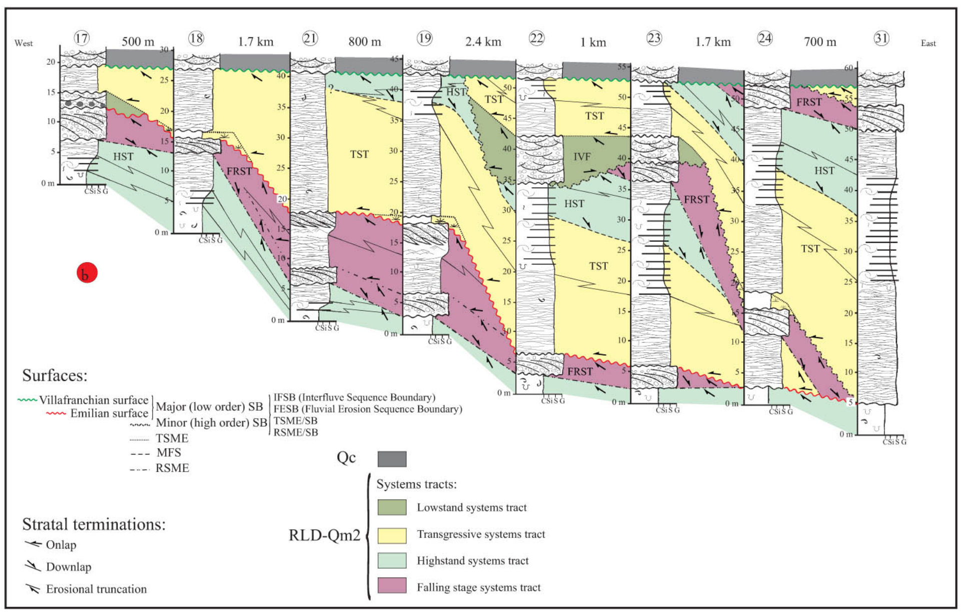


Figure 5. A large-scale uplift motion combined with glacioeustasy drove the progressive shallowing of the basin fill. The major influence of regional uplift on stratal accumulation is on longer term, at sequence set scale and is responsible for sequence arrangement. High-frequency sequences are laterally stacked in a strongly progradational pattern, indicating deposition under overall conditions of low accommodation. The progressive eastward and downward migration in maximum shoreline position of successive sequences indicates that each sequence marks a successive basinward step in the overall regressive pattern of the Qm-Qc succession and that they are nested to form a longer-order falling-stage sequence set. This means that each sequence represents the signature of eustatic sea-level variations, and that although synsedimentary tectonic uplift did not alter the trend of shoreline displacement within a single glacio-eustatic cycle, it drove the long-term trend of the sea-level changes at a multicycle time scale and, therefore, the vertical arrangement of successive sequences.

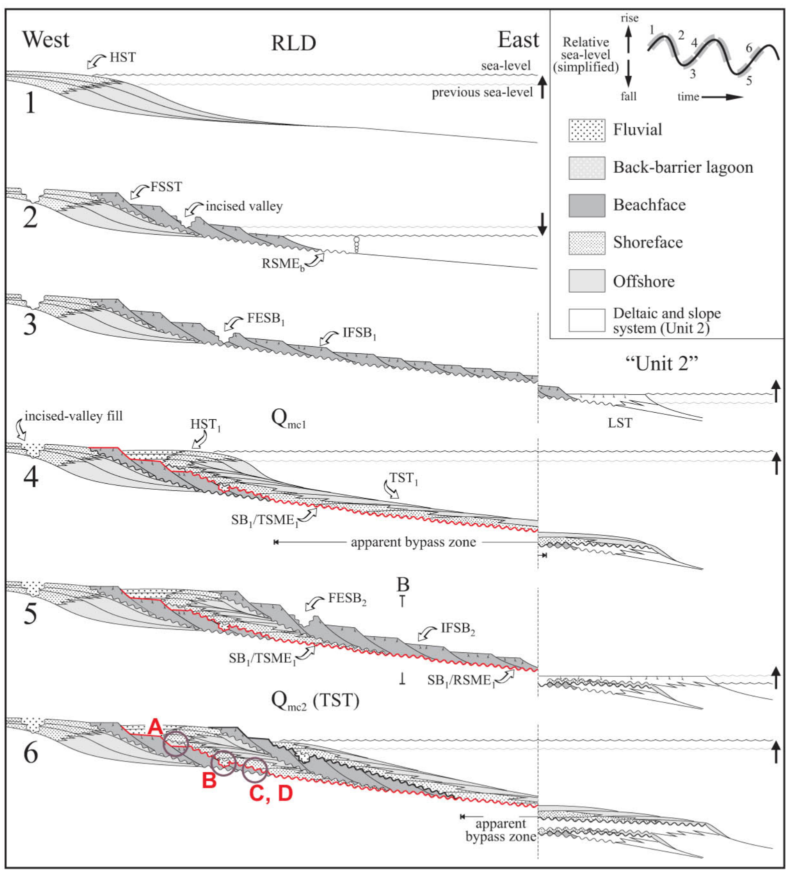
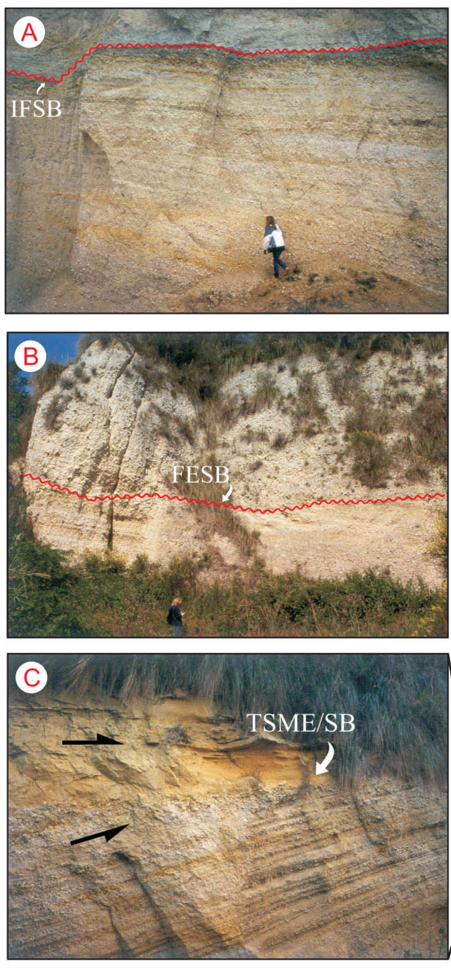


Figure 6. Sketch illustrating the composite nature of the Emilian surface, sequence stacking pattern and systems tract architecture within RLD-Qmc. Each high-frequency sequence, composed by late LST, TST, HST and FSST, is detached from the early LST (Unit 2 of Ori et al., 1986) by an apparent sediment bypass zone generated by wave erosion during the ensuing transgression. Note that TST and HST dominate the more landward sites, whereas in relatively basinward sites the FSST can represent the entire depositional sequence.



Outcrop photographs of different stratal expressions of the Emilian unconformity. **(A)** Seaward-dipping (toward the right) beachface deposits and interfluve surface of subaerial exposure (IFSB1) succeeded by back-barrier green clays and silty clays. The interposed paleosol testifies to pedogenic processes during a period of lowstand subaerial exposure and weathering of the continental shelf. Since paleosols are inferred to be produced on low-relief interfluve areas during periods of baselevel fall and landscape stability, it represents a non-depositional hiatus in the sedimentary record and is interpreted as the interfluve sequence boundary (IFSB) separating Qm1 from Qm2. **(B)** Prograding beachface gravels at the top of RLD overlain by an erosively based, lenticular and non-marine gravel-body, which is clearly incised into the underlying deposits (IVF). This contact is a basinward shift in facies marking a sequence boundary but, because the FSST is directly overlain by fluvial gravels, there is no clear physical evidence of subaerial exposure along the contact. **(C)** Clinostratified beachface gravels within RLD truncated and abruptly overlain by onlapping marine sands. Shoreface erosion during landward movement of the shore-connected sedimentary prism stripped off the evidence of subaerial exposure and resulted in the superposition of TSME1 upon the sequence boundary and the development of the composite surface SB1/TSME1.

(D) The base of the clinostratified beachface gravels is a sharp erosion surface truncating the undetlying offshore mudstones. Note the angular unconformity across this surface and the onlapping stratal termination of the lower shoreface sands overlying the gravels.

Measured Section 15. Note the seaward (to the left) and downward migration of the beachface gravel body occurring at the top of RLD and interpreted as falling stage systems tract. The upward sequence of facies associations is interpreted to reflect an overall forestepping-backstepping of depositional environments due to a relative fall and successive rise of sea level.

Short- and long-term tectonic control on internal architecture and stacking pattern of Pleistocene depositional sequences (Mejillones Formation, northern Chile)

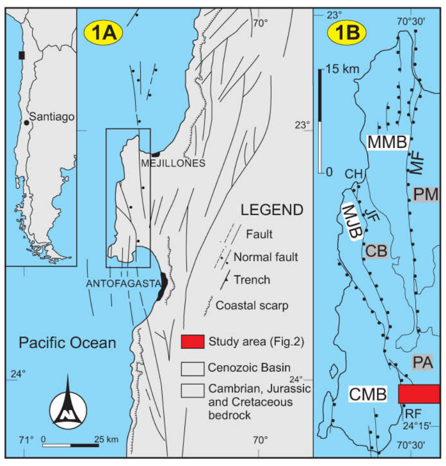


Figure 1. Map of the Mejillones Peninsula. A) Regional tectonic setting of the Mejillones Peninsula area modified by Niemeyer et al. (1996). B) Tectonic sketch map of the Mejillones Peninsula showing distribution of main geological features. MMB, Morro Mejillones Block; CMB, Cerro Moreno Block; MJB, Morro Jorgino Block; MF, Mejillones Fault segment; JF, Jorgino Fault strand; RF, La Rinconada Fault strand; PM, Pampa Mejillones basin; CH, Caleta Herradura subbasin; CB, Cerro Bandurrias subbasin; PA, Pampa del Aeropuerto subbasin.

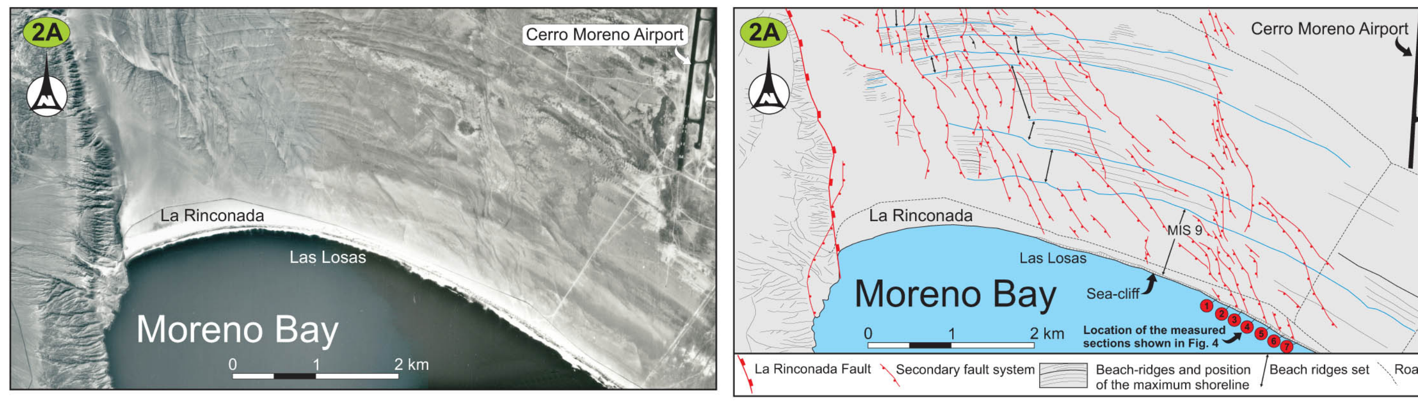
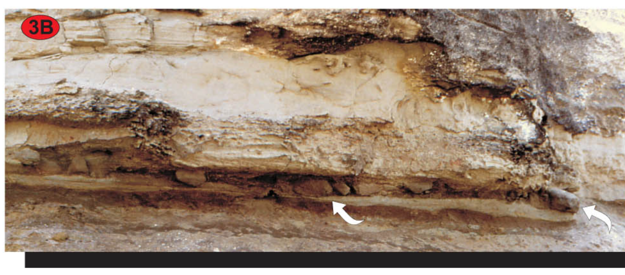
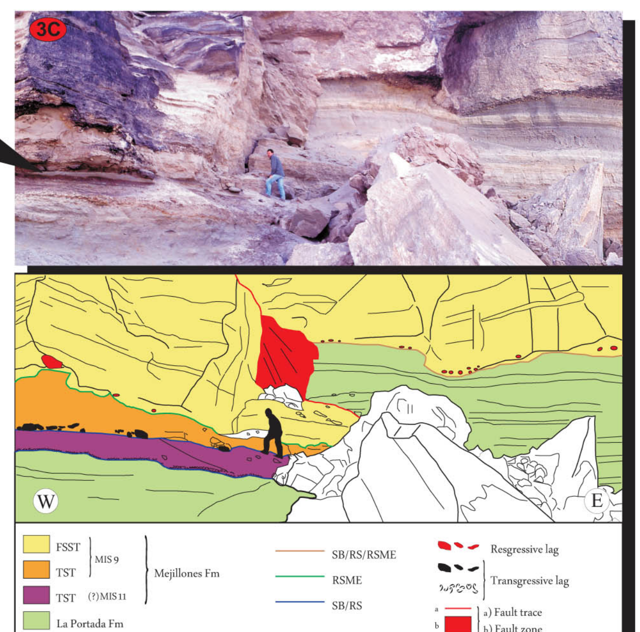
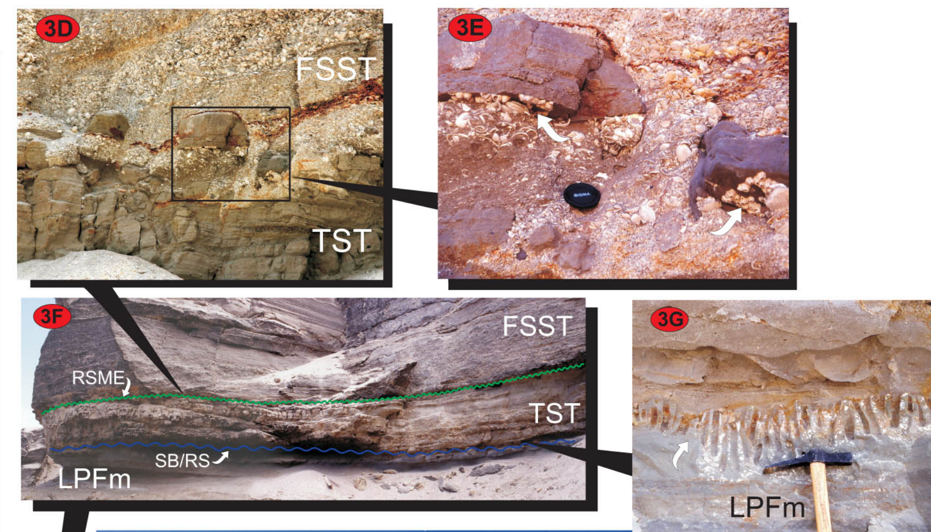
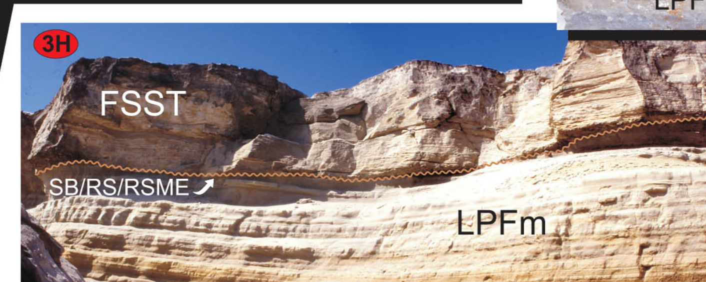


Figure 2. A) Aerial photograph and B) line drawing of the Moreno Bay and the adjacent Pampa del Aeropuerto plain, showing the major faults of the secondary system and beach-ridge sets. The height of the sea-cliff diminishes progressively westward as a result of a recent roll-over into the halfgraben-bounding fault (La Rinconada fault strand). Note that each successively younger beach-ridge set extends less far inland than the older one and that the series of normal faults of the secondary system are oriented obliquely with respect to the palaeoshore trend (indicated by beach-ridges) and cut the sea-cliff along the stretch of coast to the east of Las Losas.









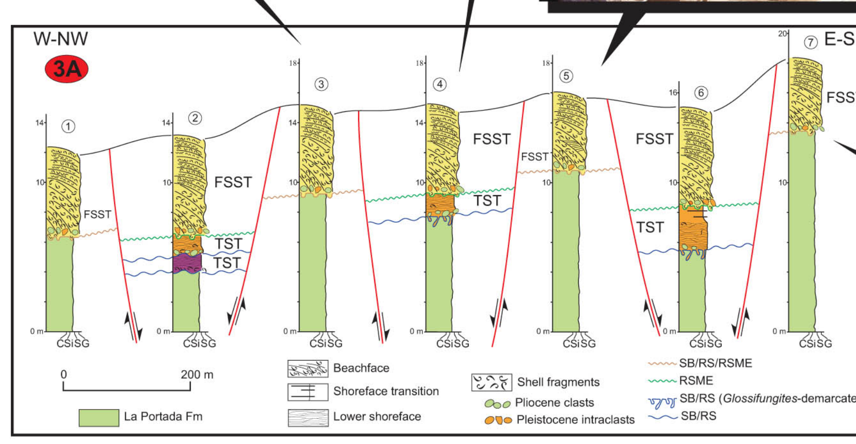


Figure 3A. Depositional strike-oriented correlation panel of the studied section showing a synthesis of distribution of systems tracts both at the hanging-wall and footwall of the secondary normal fault system. These simplified stratigraphic sections were measured along the continuous exposures of the Moreno Bay coastal-cliff (see Fig. 2 for locations).

Figure 3B. Pebble- to cobble- grade conglomerates along the base of the TST (see white arrows) representing a transgressive lag.

Figure 3C. Photograph and line drawing of an outcrop view east of Las Losas, showing the abrupt lateral variation in sequence architecture encountered across the normal faults. About 10 m of section oriented normal to depositional dip is shown. Relative displacement across the fault is about 5 m. The complete transgressive-regressive architecture of the studied sequence (MIS 9) is preserved in hanging-wall sections (to the left of the geologist) whereas only its regressive portion is preserved in footwall sections (to the right of the geologist). In this case, owing to the high subsidence of the hanging-wall, also the transgressive deposits of an older depositional sequence (MIS 11?) is preserved.

Figure 3D. Close view of the contact between the transgressive systems tract (TST) and the falling stage systems tract (FSST) showing the presence of a discontinuous lag of angular, ripped up sandstone intraclasts. Note the coarse and tightly packed mollusc skeletons that characterise the lower part of the FSST.

Figure 3E. Enlargement of Fig. 3D showing detail of angular sandstone clasts occurring along the lower part of FSST. They are encrusted by barnacles on the lower side (white arrows). This position of barnacles is untenable for life (their apertures would have been forced into the sediment), implying overturning of the clasts after the barnacles grew on the upper surface.

Figure 3F. Outcrop photograph of a hanging-wall section (measured section 4 in Fig. 3A). Here, the Mejillones Formation contains both the TST and FSST and the lower sequence boundary consists of a transgressively modified surface of subaerial exposure (SB/RS).

Figure 3H. Outcrop photograph of a footwall section (measured section 5 in Fig. 3A). At the footwall only the FSST is preserved and the sequence is bounded below by a regressive surface of marine erosion superimposed upon the previous transgressively modified sequence boundary (SB/RS/RSME).

Figure 3G. The white arrow points to the abundant shafts of ichnogenera *Psilonichnus* and *Skolithos* (Glossifungites ichnofacies) subtending from the surface interpreted as the ravinement surface (RS) coplanar with the sequence boundary (SB). The RS removed any evidence of previous subaerial exposure. Note the vertical, sharp-walled and unlined nature of the traces indicating the firmness of the substrate at the time of burrow excavation. Tube diameters reach 1.5 cm.

Figure 3I. Strike-oriented view of the abrupt contact between sediments of La Portada Formation and the overlying FSST. Note the presence of a series of 10-20 cm deep and 30-50 cm wide gutter casts along the base of the FSST.

Short-term tectonic control on sequence architecture

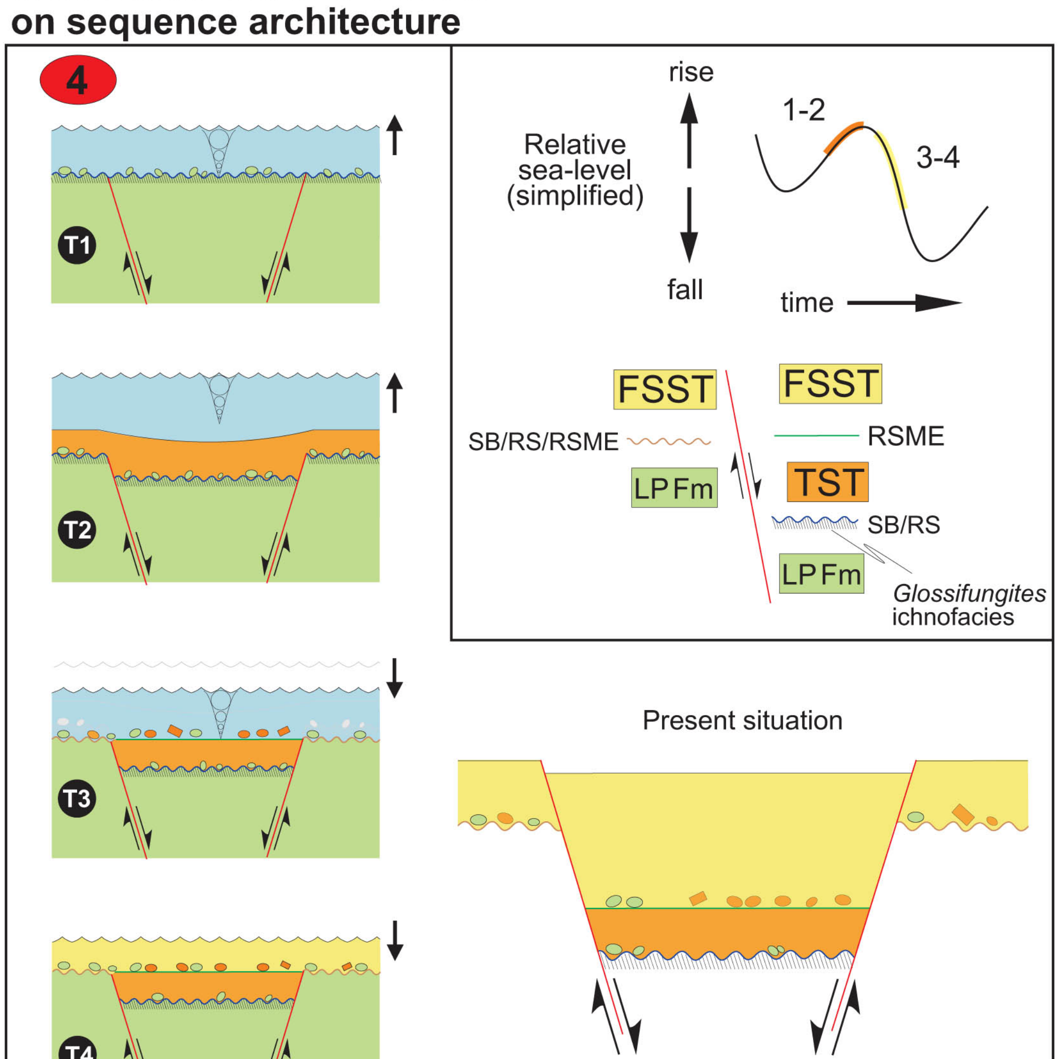


Figure 4. Schematic model that helps to explain variations in sequence architecture across normal faults in response to locally varying accommodation. At time T1, during a rapid sea-level rise and landward migration of coastline, the subaerial surface of exposure (SB) was eroded and replaced by a *Glossifungites*-demarcated RS (coplanar SB/RS). At T2, as transgression proceeded, new accommodation was created, more sediment was added to the rock record, and a relatively thin TST was deposited. At such time, incremental fault movement resulted in uplift of footwall blocks and subsidence of hanging-wall blocks. During the succeeding longer-lasting phase of sea-level fall, accommodation was progressively destroyed in response to sea-level lowering. Wave scouring in front of the advancing shoreline cut and smoothed the antecedent fault-generated sea-floor morphology and the poorly consolidated, recently deposited sediments were quickly eroded, leaving an intraclast lag on the unconformity surface (RSME) (T3). Under these circumstances, depending on the hanging-wall or footwall setting, two different sequence architectures were generated. At the hanging-walls, because of net subsidence, wave scouring attained a position that was relatively shallower than that reached during transgression, so that only part of the TST was eroded during formation of the RSME. At the same time, the positive surface relief of footwall highs start being eroded, reworked, and removed by wave scouring until the floor was reduced to the same level as that in the hanging-walls. However, because of the relative uplift of footwall blocks, this position was deeper than that reached during transgression. Consequently, the entire TST and part of the underlying Pliocene bedrock were eroded from the crest of footwalls, forming a tectonically enhanced, coplanar regressive surface of marine erosion and sequence boundary (SB/RS/RSME).

Long-term tectonic control on sequence stacking pattern

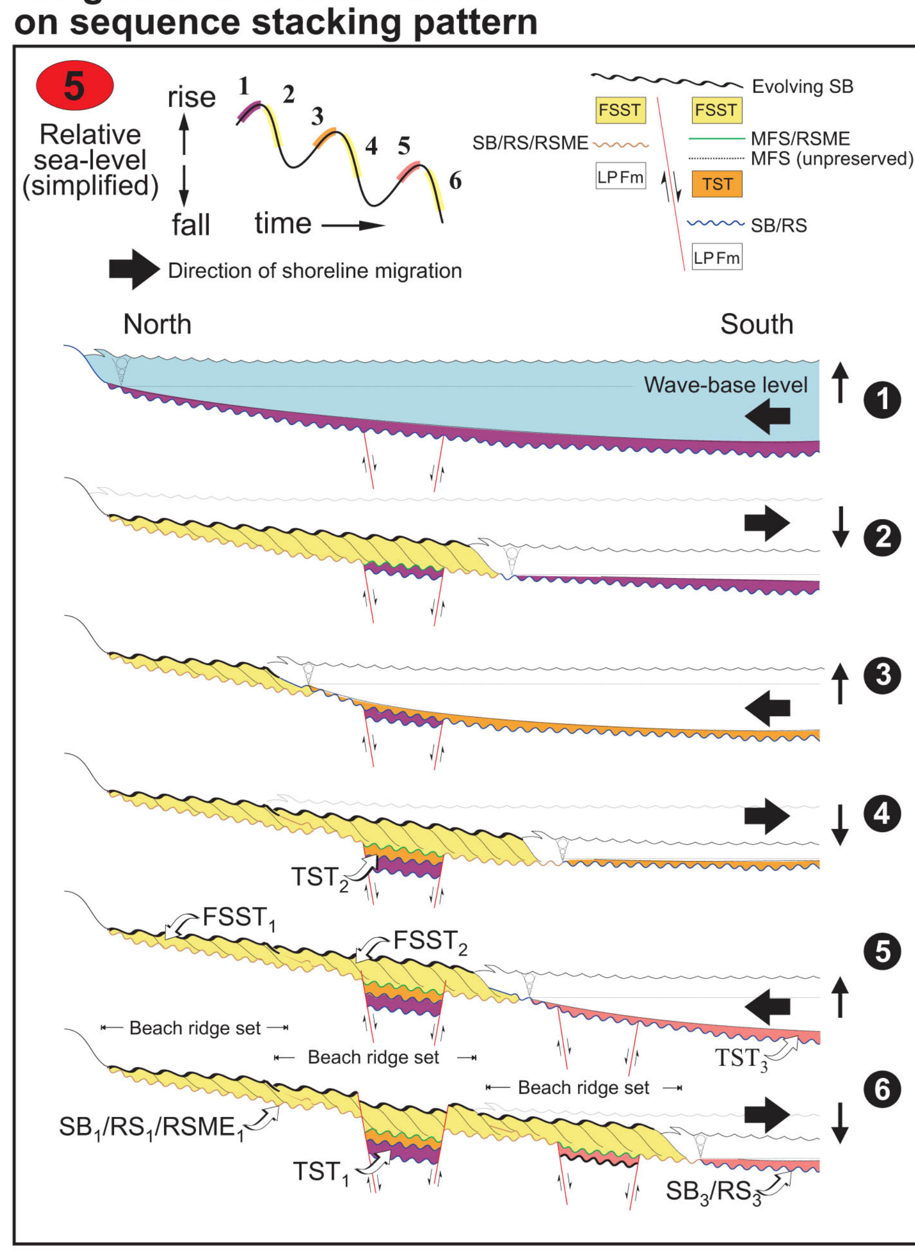


Figure 5. Generalised depositional dip-oriented sketch (no scale implied) illustrating a conceptual model for the development of systems tracts and bounding surfaces down the axis of the gulf. The overall progradation of the Pampa del Aeropuerto strandplain occurred through forced regressions and intervening landward shifts of shoreline controlled by glacio-eustatic, high-frequency oscillations superimposed on a tectonically-driven long-term sea-level fall. Sequences, which may have been partially destroyed by subaerial processes during the emergence stage and erosional ravinement during the next transgression, are stacked in an downstepping configuration and, as a whole, represent a tectonically enhanced, falling-stage sequence set. Boundaries of older sequences, that formed during sea-level fall, sub-aerial exposure of the shelf and subsequent sea-level rise and erosional reworking, are truncated downdip by the successive erosion surface. Consequently, the falling-stage sequence set is bounded below by a complex surface that develops diachronously from the down-dip merging of successive composite sequence boundaries.